Large jets from small-scale magnetic fields

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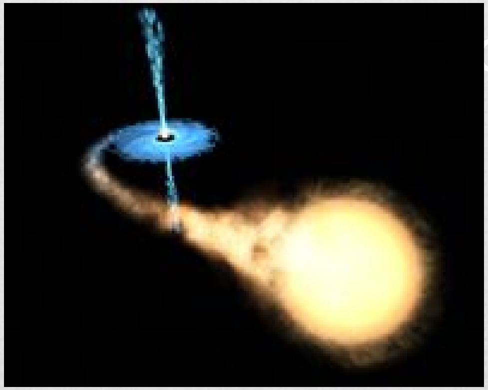
Relativistic Jets: Creation, Dynamics and Internal Physics
Krakow, April 20-24

Relativistic jets from black holes and disks of all sizes/powers

jets in galactic centers


M87; NASA/Hubble

X-ray binaries



gamma-ray bursts

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Second level

Third level

Fourth level

Fifth level

MBH~109M⦿

~10M⦿

~3M⦿

Power~1044...1049erg/s

~1038erg/s

~1052erg/s

Basic Observed properties

Efficient radiators ~10% radiative efficiency or more!

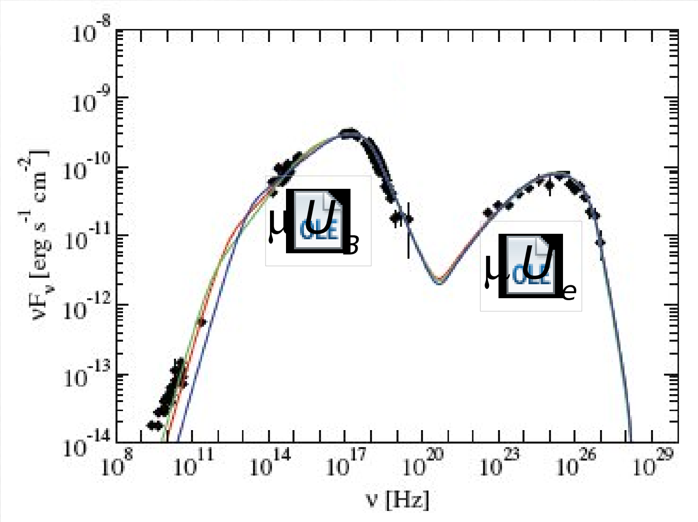
Effective particle accelerators up to multi TeV energies, *at least*

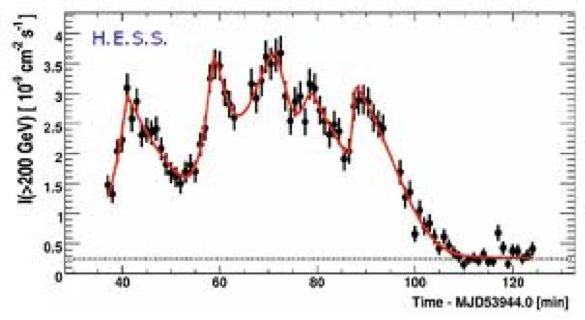
Radiating particles and magnetic field in very rough equipartition:

$U_e \sim U_B$

Other properties: highly variable (t<Rg/c), interesting polarization swings…

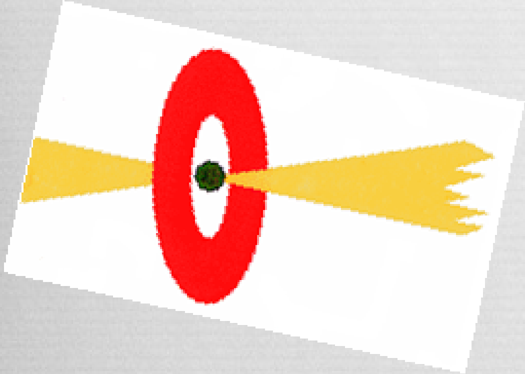
SSC model fit of the spectral energy distribution of Mrk 421

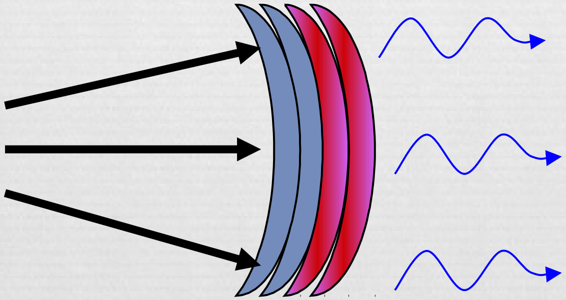




How is the jet flow launched?

jet emission $U_e \sim U_B$





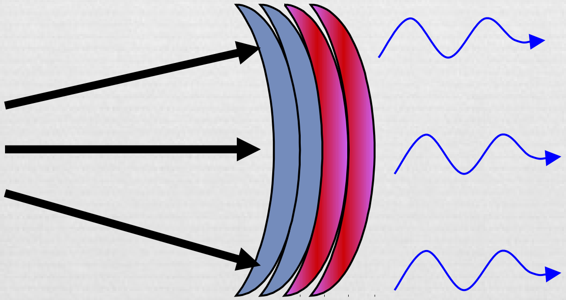
Central
engine

Acceleration

Internal
dissipation

How is the jet flow launched?

jet emission $U_e \sim U_B$???



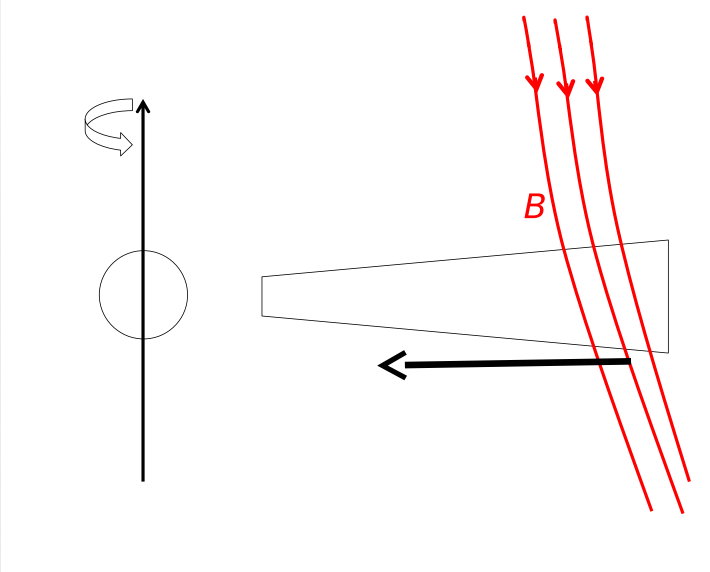
Acceleration

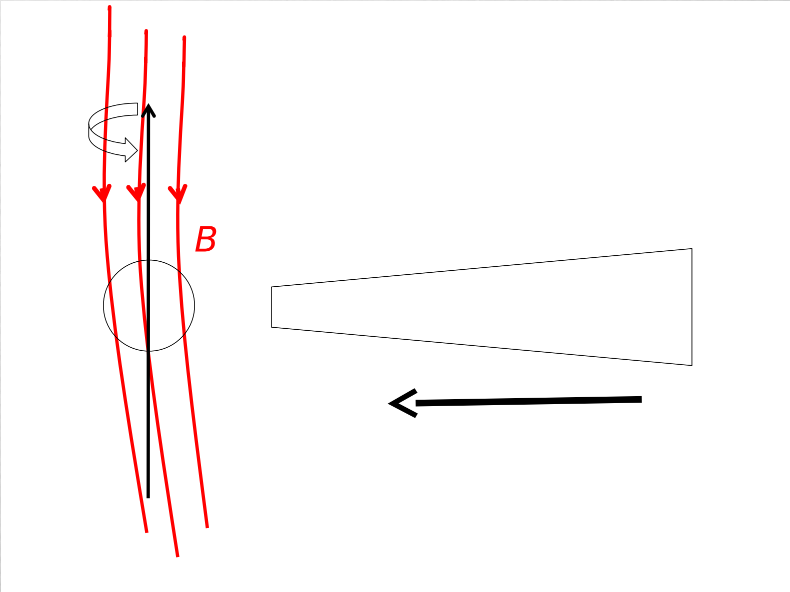
Internal dissipation

Blandford & Znajek 1977
Begelman & Li 1992
Meier et al. 2001
Koide et al. 2001
van Putten 2001
Komissarov, Lyubarky, McKinney, Tchekhovskoy
…

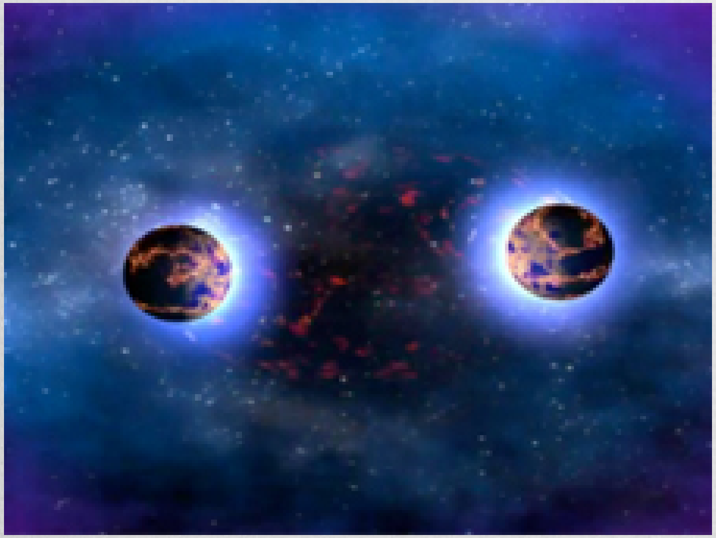
$$\sigma_{initial} = \frac{B^2}{4\pi\rho c^2} >> 1$$

Origin of magnetic fields: carried in from large scales?

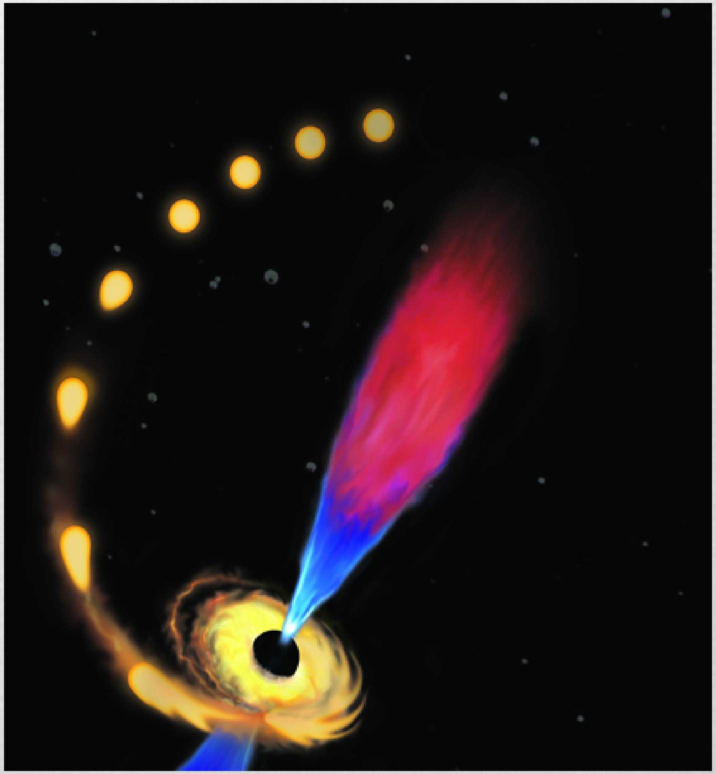




When the fields at the progenitor are ***not*** sufficient



binary neutron star mergers:
Short GRBs



Stellar Tidal Disruption Jets (J1644)
Giannios & Metzger 2011; Bloom et al. 2011

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annios, Beloborodov 2015

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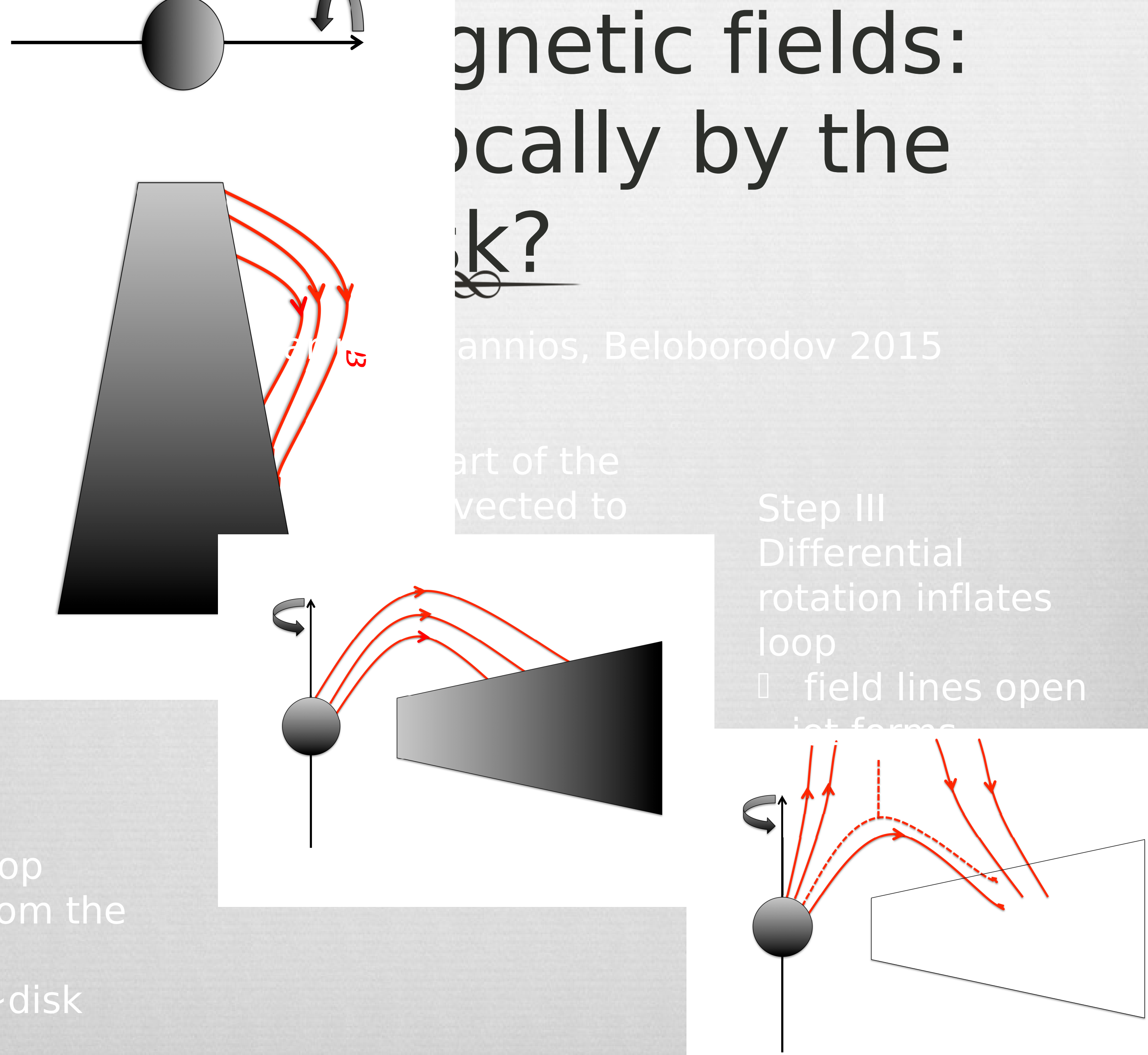
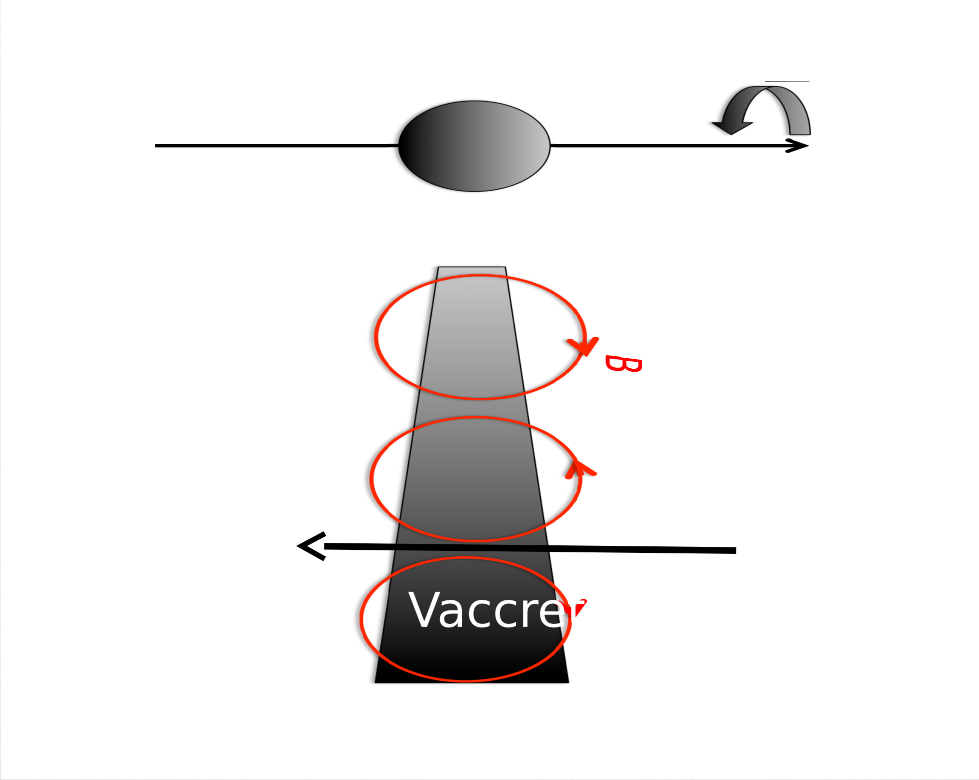


Step III
Differential rotation inflates loop
 field lines open

Step I
magnetic loop emerging from the disk
loop scale ~disk scale hight

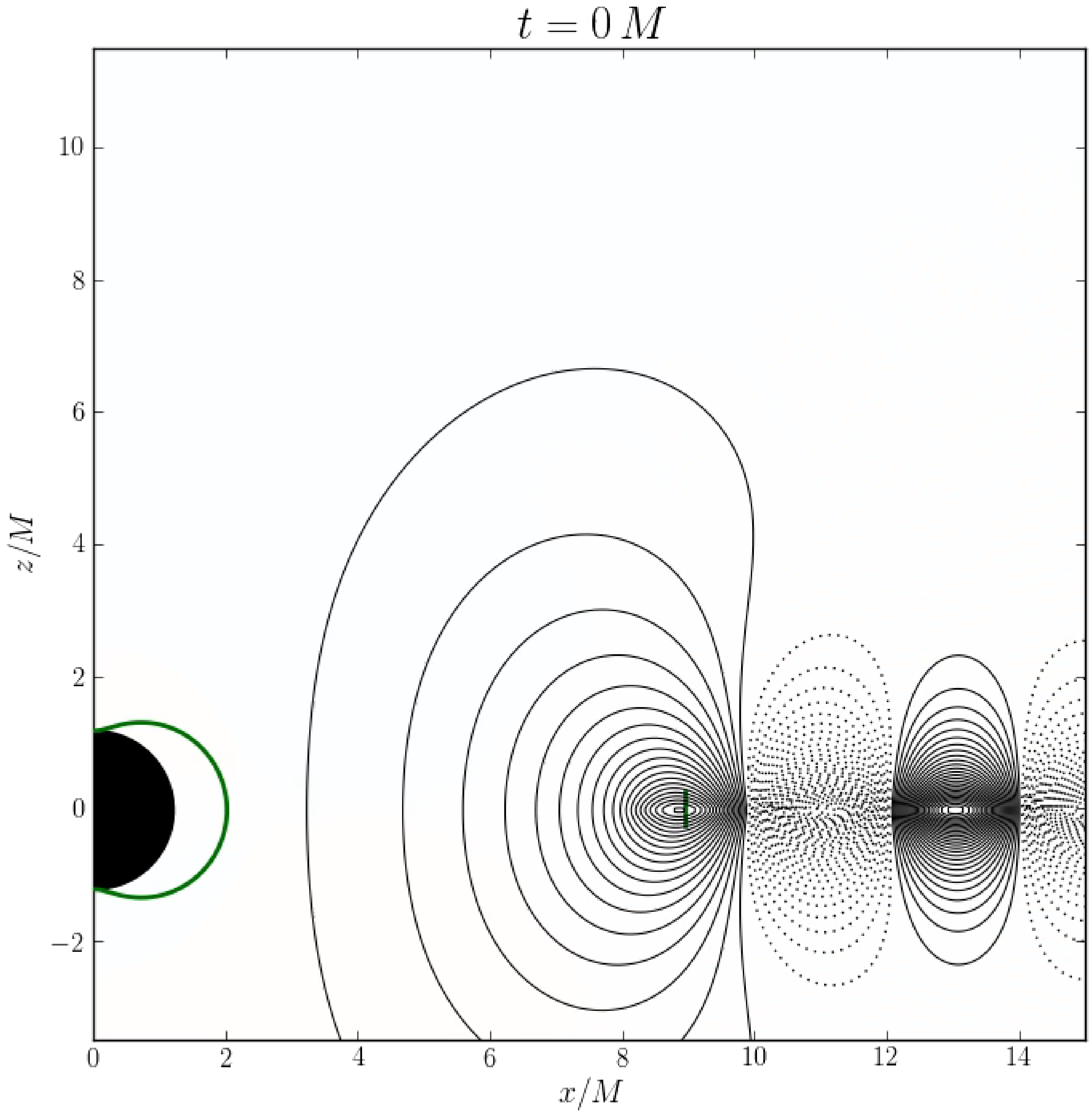
GR (force free) MHD simulations

Parfrey, Giannios, Beloborodov 2015



Retrograde disc

Parfrey, Giannios, Beloborodov 2015



loop width = 2 *rg*

loop direction

clockwise

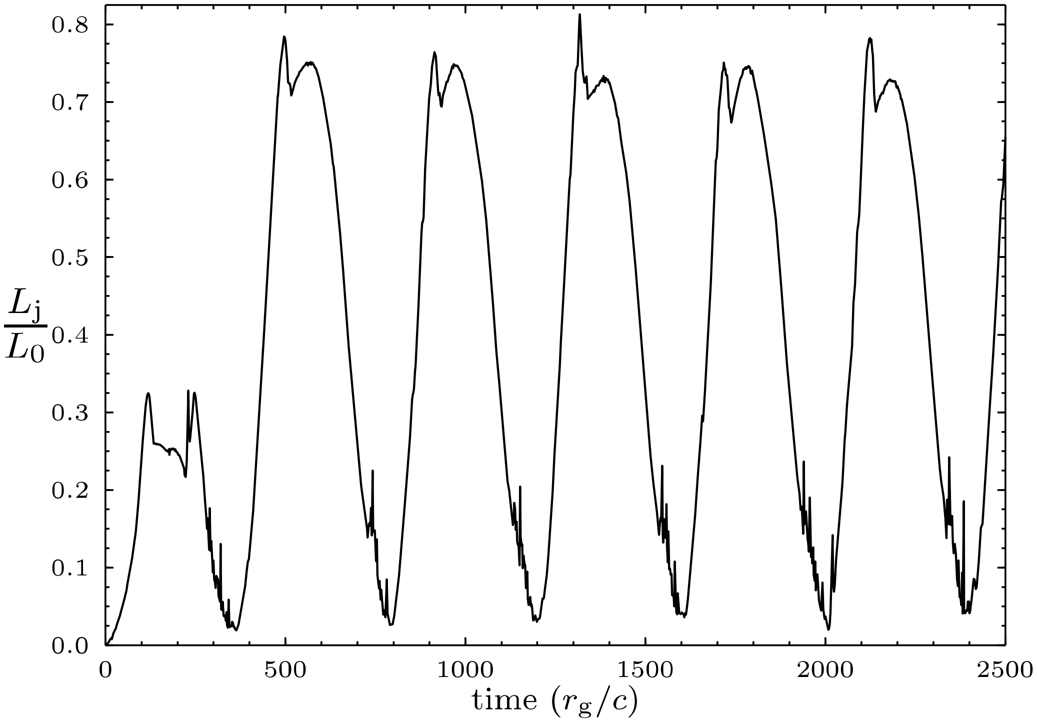
anti-clockwise

Colour: $H\phi$ positive negative

$$v_{\mathrm{accrete}} = c/100$$

$$a/M = 0.98$$

The jet power



The Jet Power (continued)

$$L_j \propto \frac{\Phi^2 a^2}{R_g^2} c, \quad \Phi = 2\pi r (l/2) B$$

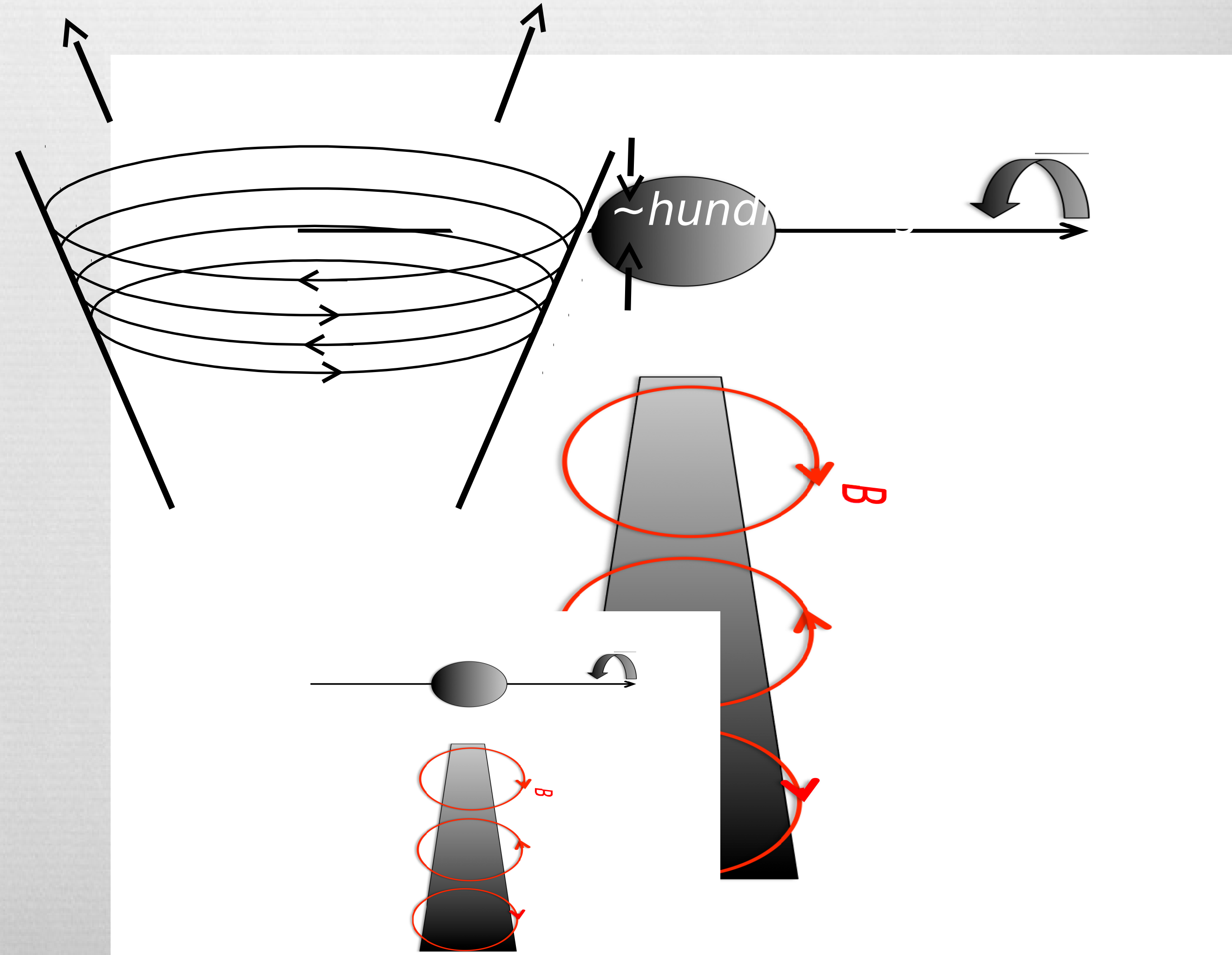
$$\frac{B^2}{8\pi} = \beta P_g = \beta \rho c_s^2 = \beta \rho \alpha (H/r)^2 v_K, \quad \dot{M} = 4\pi r H \rho v_r$$

$$L_j \approx 0.16 \boxed{\frac{H}{r}} \left(\boxed{\frac{r_{isco}}{r_g}} \right)^{3/2} a^2 \dot{M} c^2$$

For *retrograde* orbits *risco/r*g~10 and *thick*
H/r~1 disks the jet power reaches

$$L_j \sim \dot{M} c^2$$

Part II:
large scale jet and emission



Part II:
How to make you jet shine

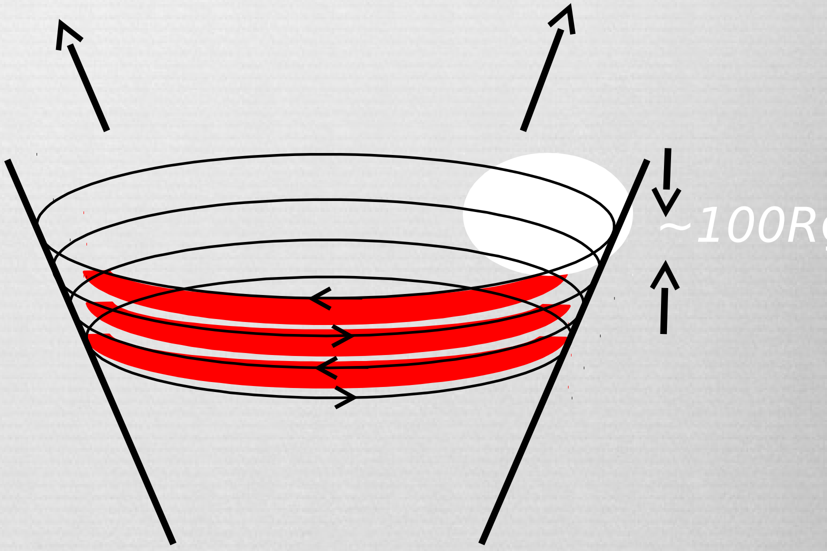
Dissipation at large scale in the jet

- Jet may contain field reversals on small scale ~hundreds *r*g
- It remains magnetically dominated
- magnetic-reconnection becomes effective when

  texp~trec

  where vrec=εc

$$\sigma = \frac{B^2}{4\pi\rho c^2} > 1$$



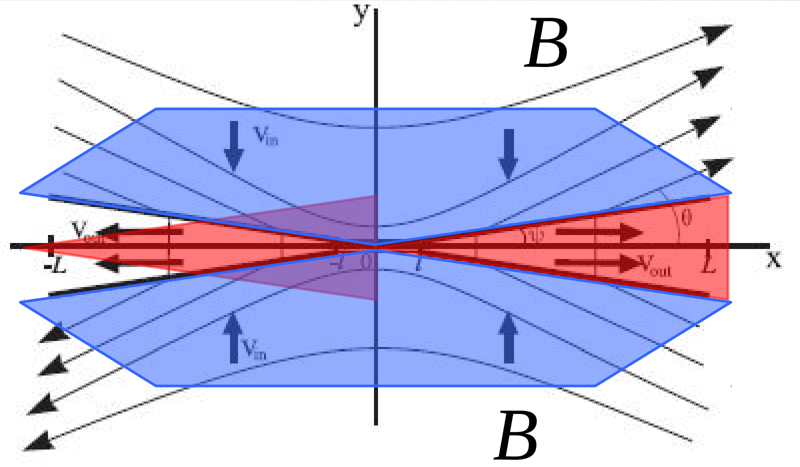
$$r_{diss} / \Gamma_j c \sim 100 \Gamma_j r_g / \varepsilon c$$

$$r_{diss} \sim \Gamma_j^2 100 r_g / \varepsilon \sim 1 M_8 \Gamma_{j,10}^2 \varepsilon_{-1}^{-1} \mathrm{pc}$$

$$t_{flare} \sim r_{diss} / \Gamma_j^2 c \sim M_8 \varepsilon_{-1}^{-1} days$$

Relativistic Magnetic Reconnection

- An efficient convertor of magnetic energy into bulk motion, heat, energetic particles
  - cold, magnetized plasma enters the reconnection region
  - plasma leaves the reconnection region at the Alfvén speed Γout~(1+σ)1/2>1
  - reconnected material contains energetic (nonthermal) particles



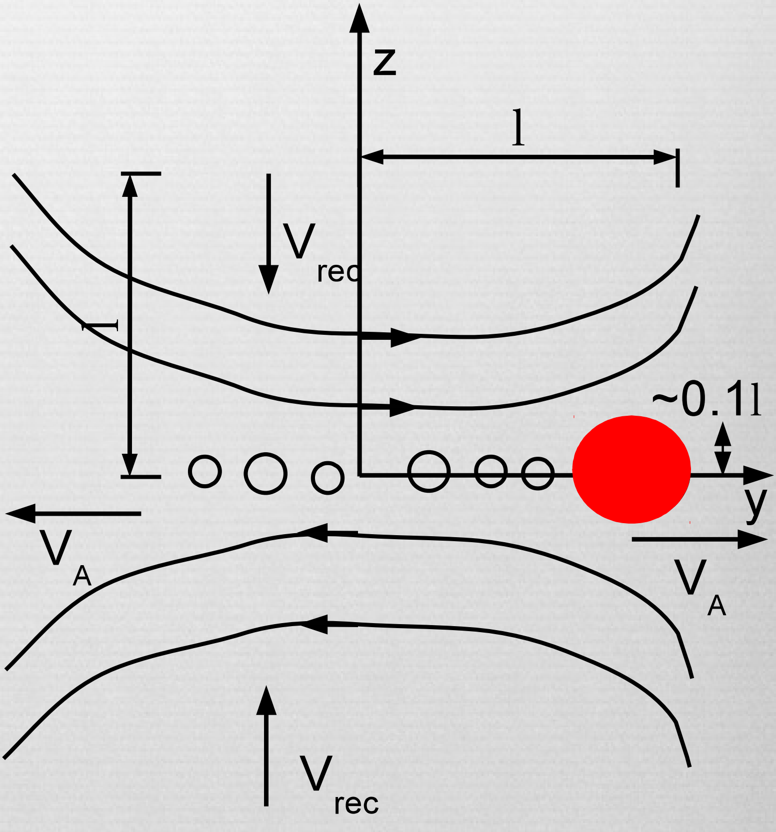
Relativistic Petschek Reconnection

Lyubarsky 2005

Reconnection downstream: emitting region

Plasmoid-dominated reconnection in blazars

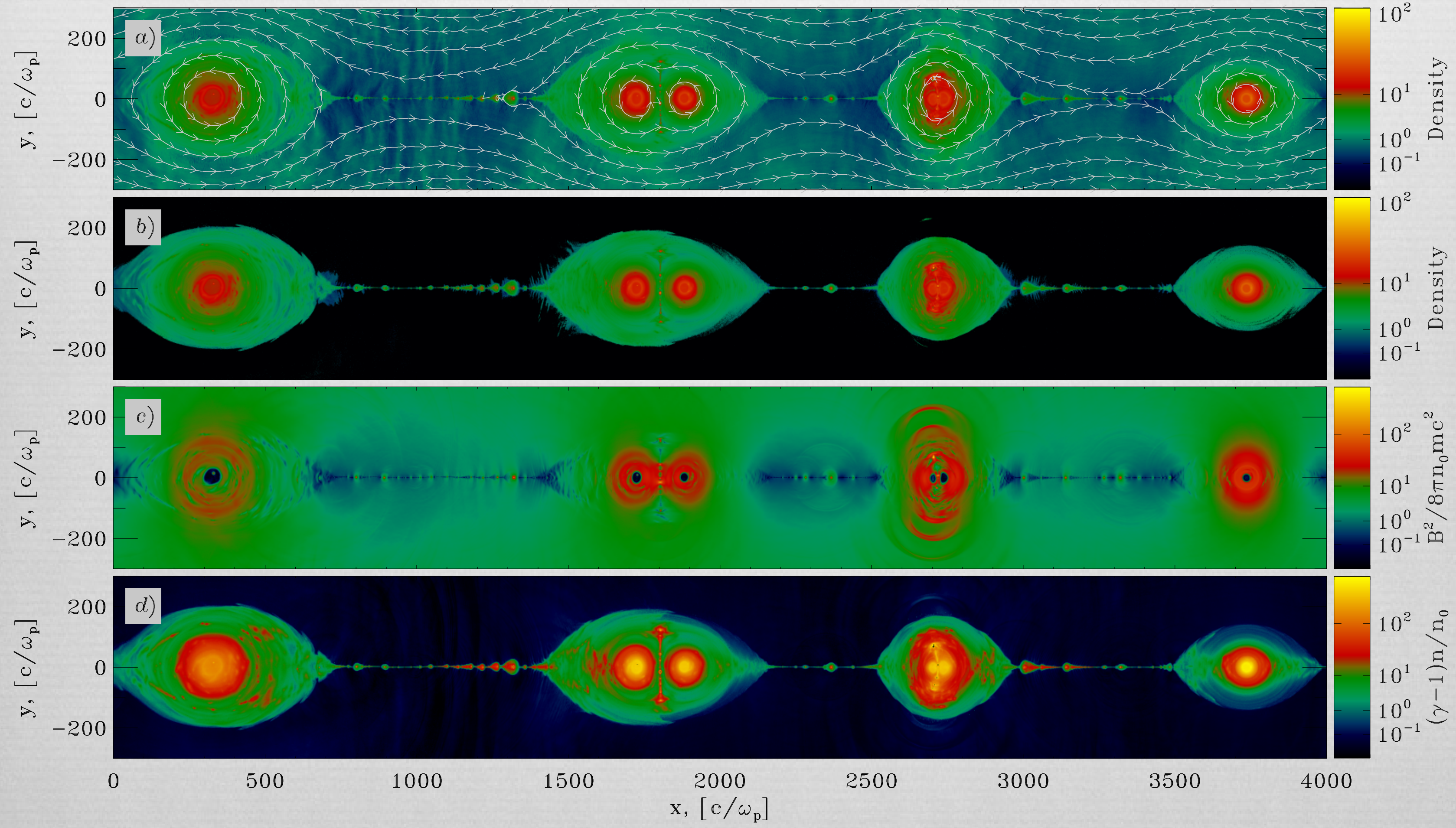
- Current sheet fragments to plasmoids
  Loureiro et al. 2007; Uzdensky et al. 2010; Loureiro et al. 2012+++
- Plasmoids merge/grow leaving the layer at VA~c
- The largest plasmoids can power bright/ultrafast blazar flares
  Giannios 2013



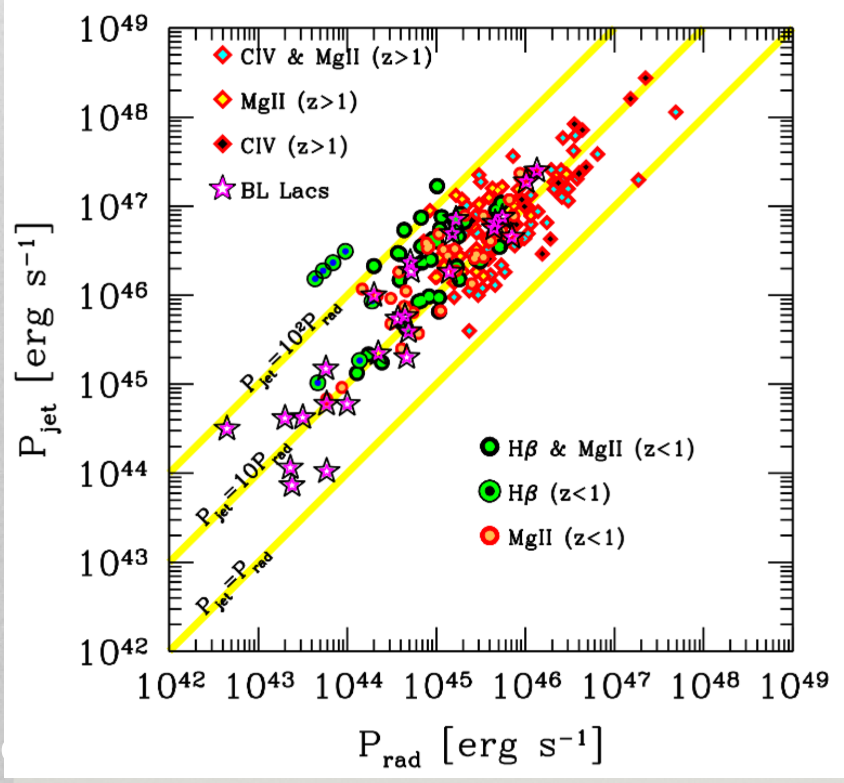
Giannios et al. 2009; 2010; Giannios 2013

Magnetic reconnection

Sironi, Petropoulou & Giannios 2015



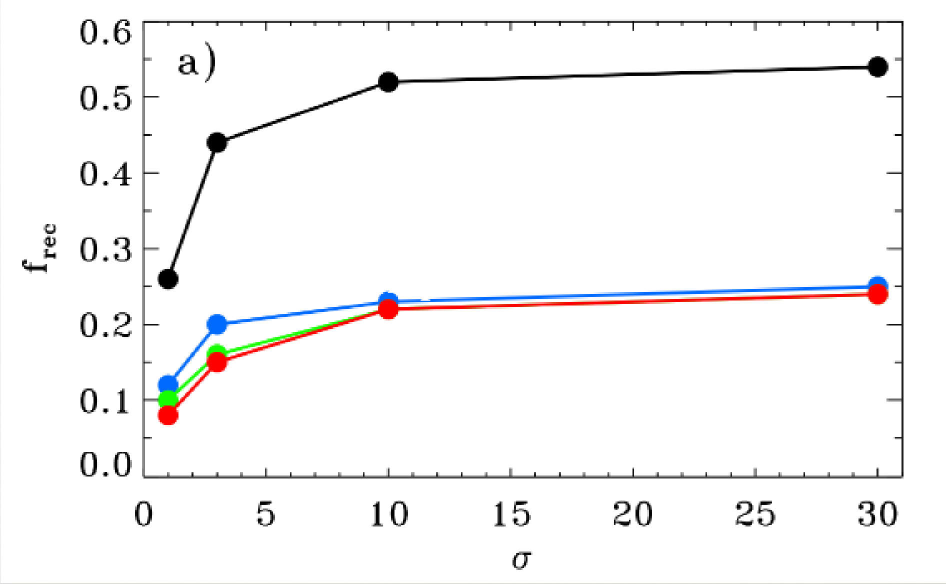
(1) Relativistic reconnection is efficient



Blazar phenomenology:

- blazars are efficient emitters (radiated power ~ 10% of jet power)

$$f_{\rm rec} \equiv \frac{\sum_i \int_{V_i} U_{\rm e} \, dV_i}{\sum_i \int_{V_i} (e + \rho c^2 + U_{\rm B}) \, dV_i}$$



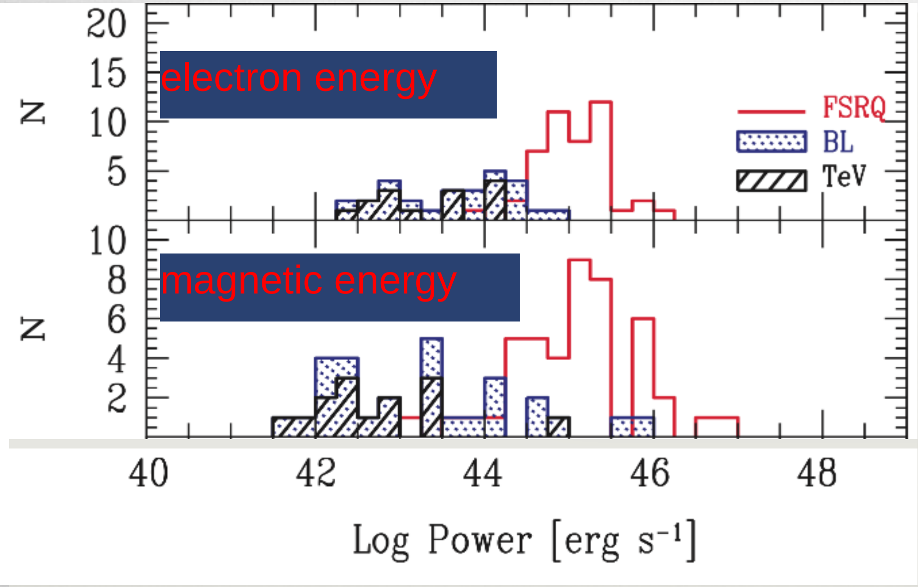
(Sironi, Petropoulou, Giannios 15)

Relativistic reconnection:

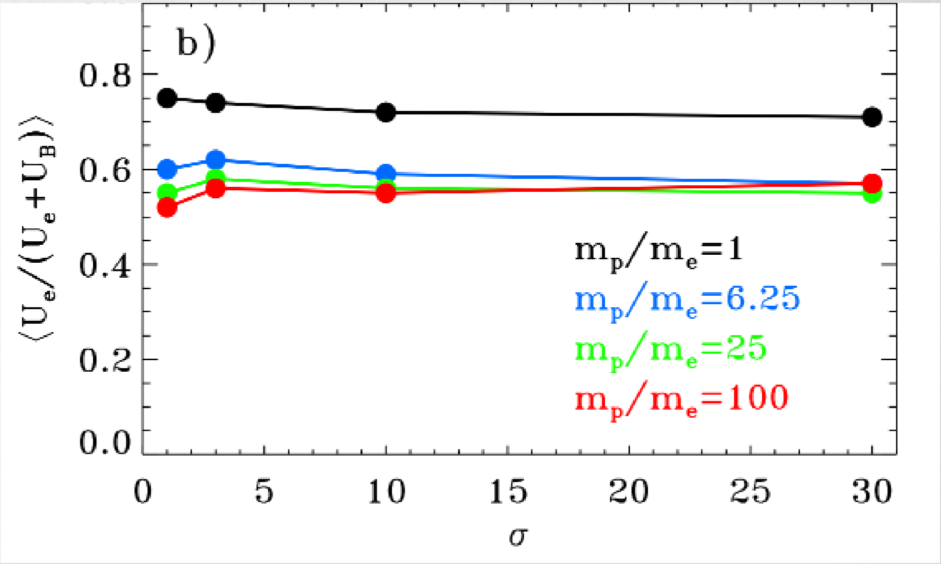
✓ it transfers ~ 50% of the flow energy (electron-positron plasmas) or ~ 25% (electron-proton) to the emitting particles

(2) Equipartition of particles and fields

$$\left\langle \frac{U_{\mathrm{e}}}{U_{\mathrm{e}}+U_{\mathrm{B}}} \right\rangle \equiv \frac{\sum_i \int_{V_i} U_{\mathrm{e}} \frac{U_{\mathrm{e}}}{U_{\mathrm{e}}+U_{\mathrm{B}}} \mathrm{d}V_i}{\sum_i \int_{V_i} U_{\mathrm{e}} \mathrm{d}V_i}$$



(Celotti+ 08)



(Sironi, Petropoulou & Giannios 2015)

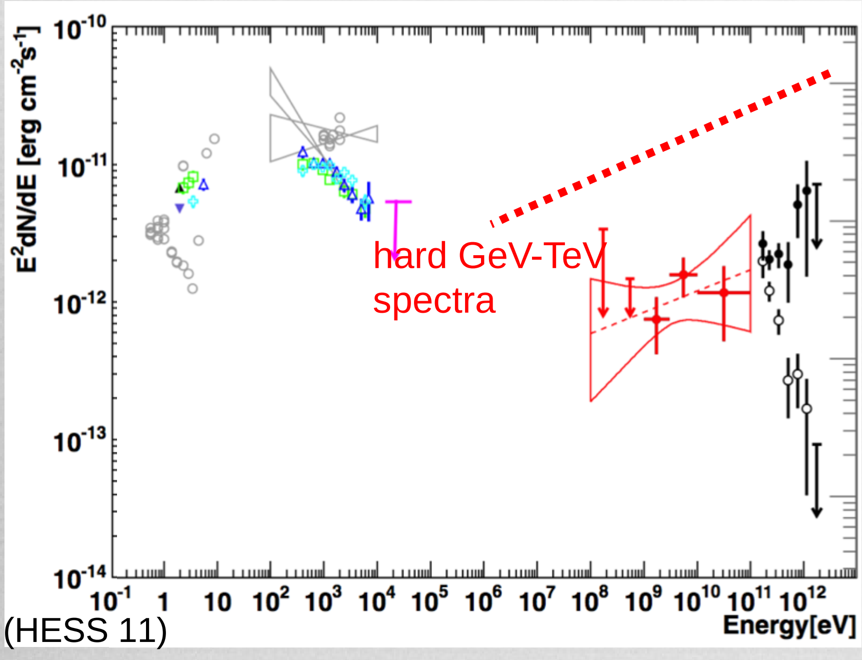
Blazar phenomenology:

- rough energy equipartition between emitting particles and magnetic field

Relativistic reconnection:

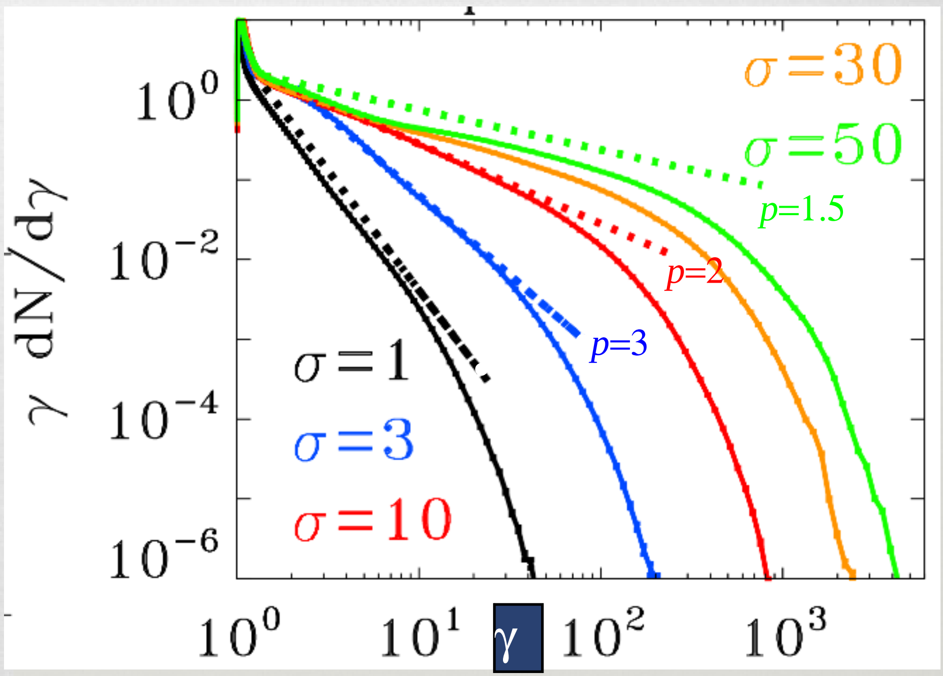
✓ in the magnetic islands, it naturally results in rough energy equipartition between particles and magnetic field

(3) Extended non-thermal distributions



hard GeV-TeV spectra

(HESS 11)



(Sironi & Spitkovsky 14, Guo et al. 14, Werner et al. 14)

Blazar phenomenology:

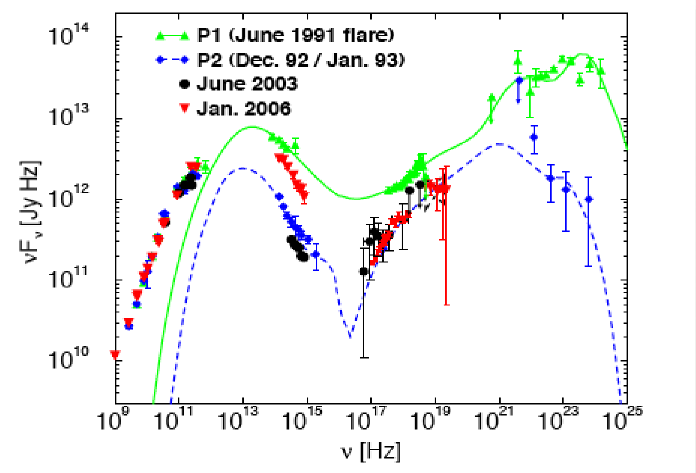
- extended power-law distributions of the emitting particles, with hard slope

$$\frac{dN}{d\gamma} \propto \gamma^{-p}, \quad p \leq 2$$

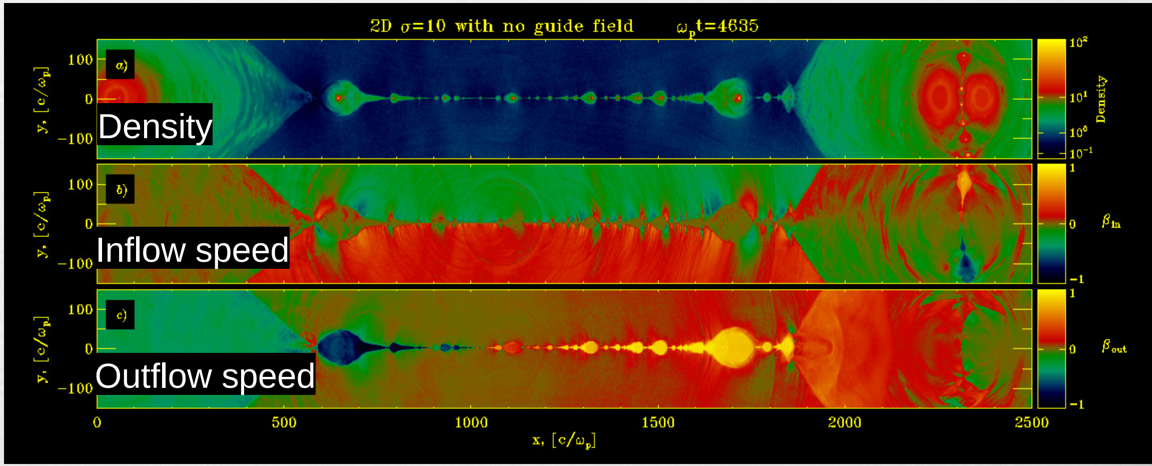
Relativistic reconnection:

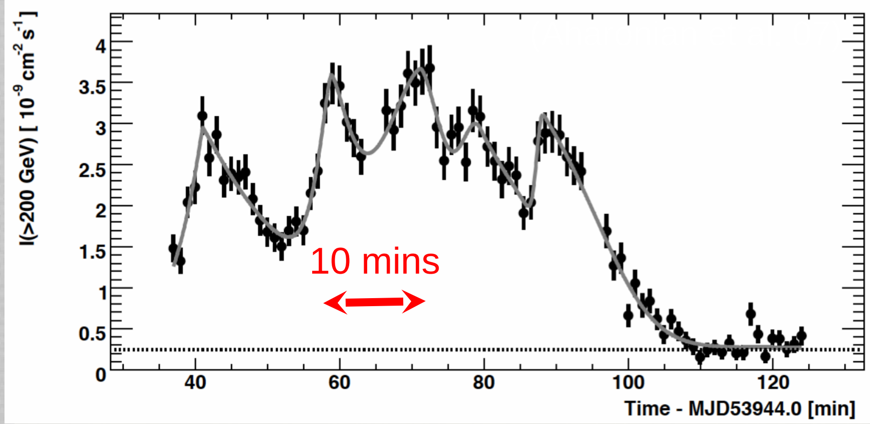
✓ it produces extended non-thermal tails of accelerated particles, whose power-law slope can be harder than *p*=2

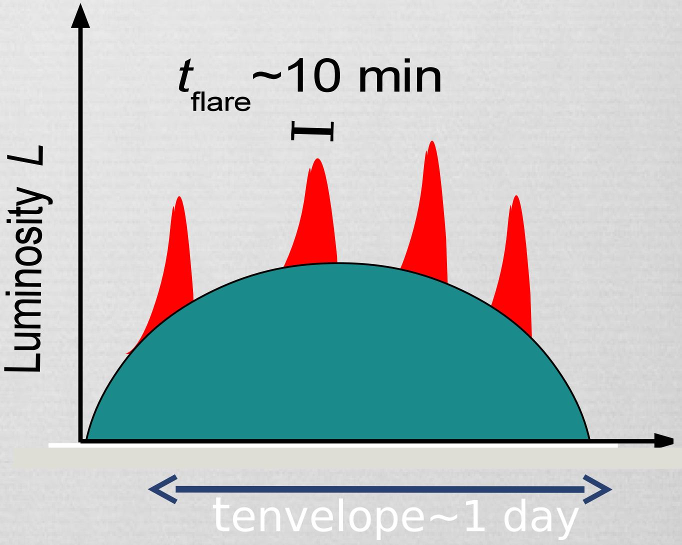
(4) Fast time variability at TeV energies



(Coppi & Aharonian 99, Boettcher 07)







Blazar phenomenology:

- at TeV energies, fast (~10 minutes) flares on a high-state envelope lasting for ~days

Relativistic reconnection:

✓ large/fast islands might be a promising source of fast variability

Shocks in jets

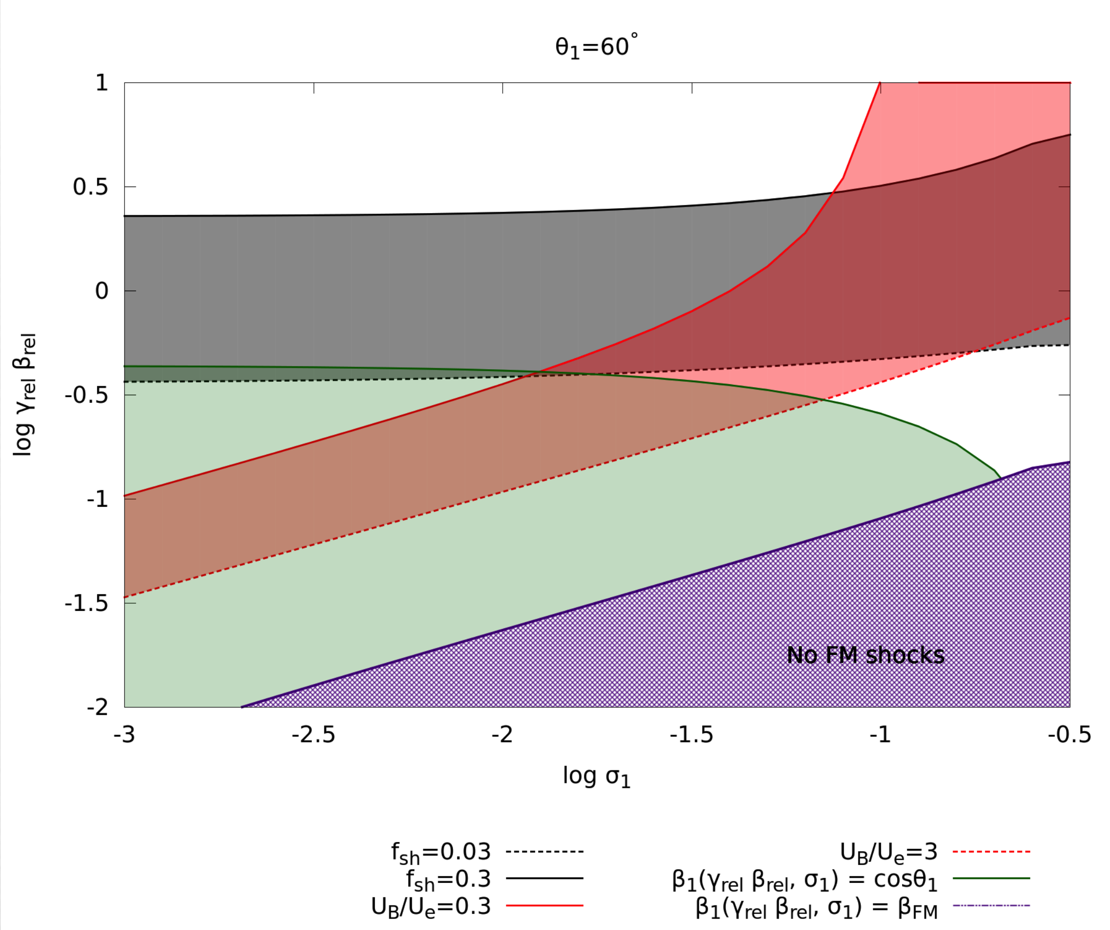
- efficiency requires that the shocks are mildly ***relativistic***, at least

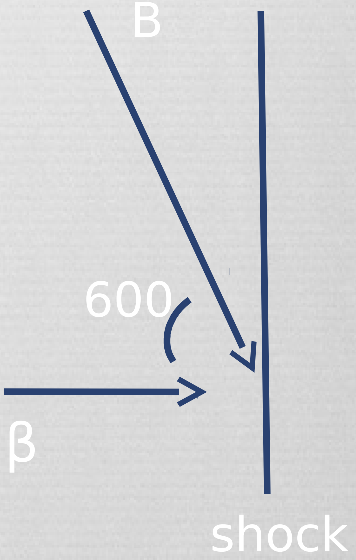
$$f_{sh} = \frac{U_e}{\rho c^2 + e} \sim 0.5\,\frac{\gamma_{rel} - 1}{\gamma_{rel}}$$

- (mildly) relativistic shocks are ***superluminal*** for most B-field inclinations
No particle acceleration

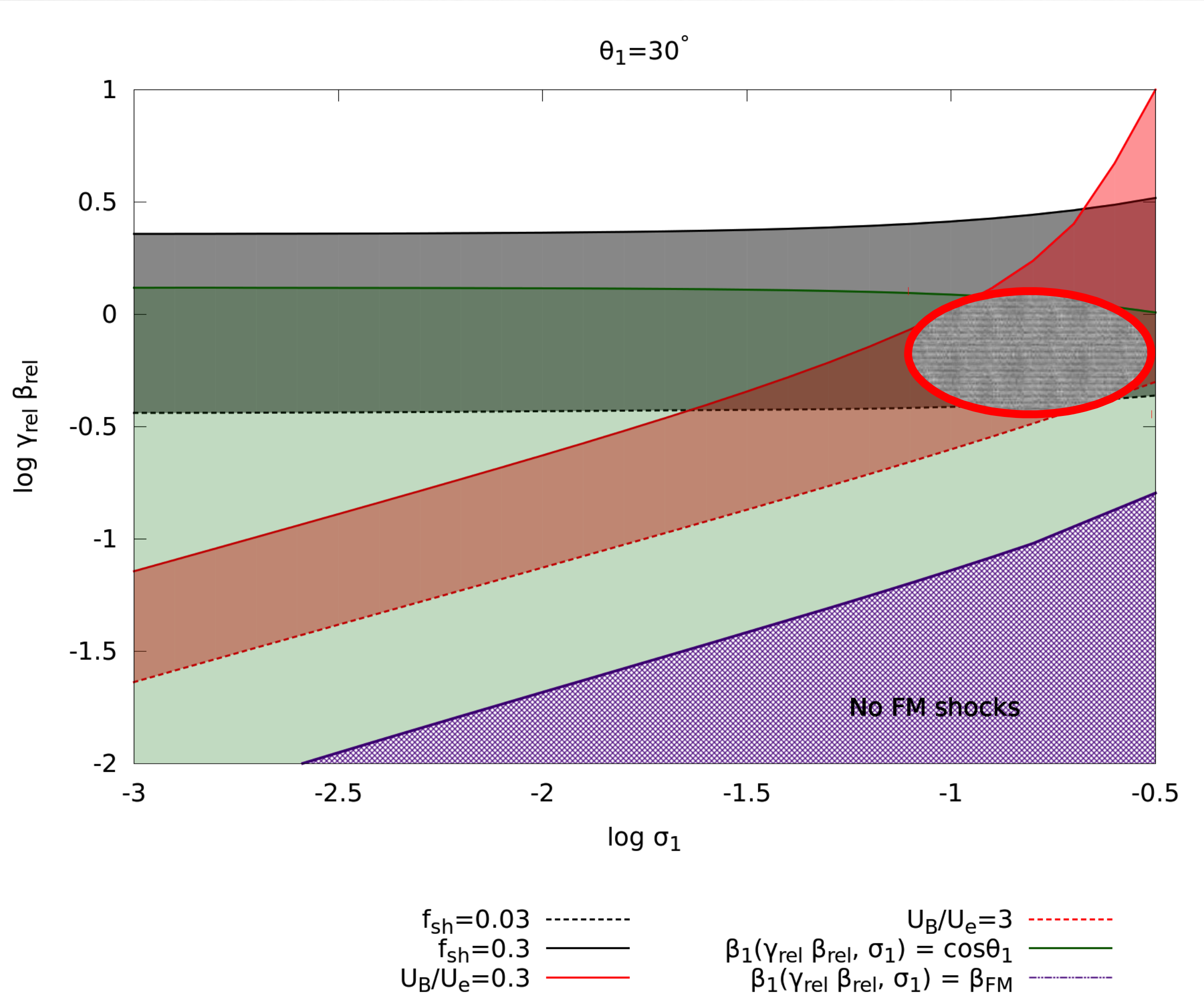
Shock is subluminal when β<cos θ

Quasi Perpendicular Shocks

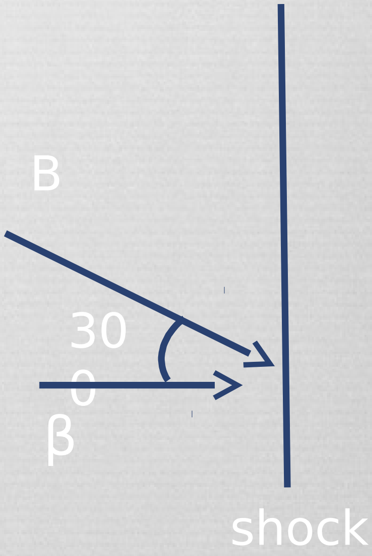




Quasi-Parallel Shocks



Sironi, Petropoulou & Giannios 2015



Concluding

- Take Home messages

1) Are large-scale fields required to make Jets?

   - locally generated fields may launch jets as well

2) Jets are observed to be efficient particle accelerators, quasi equipartition objects

   - Shocks may not be both efficient *and* accelerate particles
   - Magnetic reconnection can be both and predicts equipartition conditions at the emitting region